STATUS OF HF RADARS FOR WAVE-HEIGHT DIRECTIONAL SPECTRAL MEASUREMENTS

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Introduction

This manuscript is a concise review of the status of high-frequency (HF) radars for measuring various descriptors of the ocean wave-height directional spectrum. It is not intended as a historical account of the many developments and contributors to the subject over the past three decades; other reviews serve that purpose (e.g., Barrick, 1978; Barrick and Lipa, 1979a; Georges, 1980). Nor is it meant to develop the theory and techniques of HF radar in sufficient detail for planning HF radar programs; again, other published research papers and reports serve this purpose. Finally, no attempt is made to review every MF/HF experiment performed or analyzed, although several very clever techniques have been tried (e.g., bistatic arrangements, synthetic aperture systems, and balloon-borne antennas); rather, techniques are discussed that appear to have potential for practical, operational ocean monitoring.

The next section reviews very briefly the principles of HF radar sea echo that make it possible to measure the wave-height directional spectrum. The section following discusses the capability and status of sky-wave (over-the-horizon) radar for making wide-area ocean surface measurements. The final section discusses the application of HF ground-wave radars to measuring the wave-height directional spectrum, both for coastal use and for deployment from offshore platforms or ships, and their accuracy. In all cases, the limitations as well as the advantages of HF radars are indicated.

Background Physics

At high frequencies, the highly conducting sea favors vertically polarized electromagnetic waves, in both propagation and scattering. For sky-wave radars, where the energy incident to the ocean from the ionosphere is generally randomly polarized, vertical polarization is selected from the incoming radiation, and scattered back toward the radar. In nonionospheric propagation, as from a coastal radar out to an ocean patch 40 km from shore, vertical polarization is intentionally transmitted and received. This mode is called "ground wave" or "surface wave," in contrast to the sky-wave mode. At high frequencies, vertically polarized surface-wave radiation will propagate a considerable distance beyond the horizon of the mean spherical sea owing to diffraction. As a result, given moderate amounts of transmitted

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power (e.g., 100 W average), a coastal backscatter radar at water level can obtain usable sea echo out to a distance of 60 km from shore at a frequency of 25 MHz.

The sea is a strong scatterer of high frequencies; in fact, the backscattered power per unit area from the ocean is generally greater than that for land, even when the land includes mountains, tall buildings, or trees. It is the motion of the ocean wave scatterers, however, that gives the sea echo the unique characteristic that allows extraction of wave-height directional spectra, surface currents, and wind patterns. This unique characteristic is the spectral spread in echo energy due to the Doppler effect of moving targets.

The scattering mechanism itself is the Bragg effect. Only wave trains of a given wavelength (period) and direction of propagation--either singly or in combination--can contribute to the backscattered signal. The strength of the signal is proportional to the heights of the waves in these spectral wave trains. Since the velocity of a wave train is proportional to the square root of its wavelength, however, different wavelength/direction combinations in the wave-height directional spectrum yield their signal echo energy at unique, mathematically determinable positions in the echo spectrum.

To first order, the radar wave is backscattered by two wave trains--or Fourier components of the wave spectrum: wave trains moving toward and away from the radar whose ocean wavelengths are half the radar wavelength. This is shown schematically in Figure 1. These two wave trains produce two sharply peaked spectral echoes symmetrically placed about the transmitter frequency; their amplitudes are proportional to the heights of the wave trains moving toward and away from the radar. At 25 MHz radar frequency, these echoes therefore originate from wave trains whose wavelengths are 6 m. When a current is present, it imparts an additional common velocity to these wave trains, resulting in a further symmetrical shift of the two peaks to one side, as shown in the bottom half of Figure 1. This additional frequency shift, Δf, is directly proportional to the component of current velocity pointing toward the radar, v_{cr}. It is this latter shift, Δf, that has been exploited by HF coastal radars (Barrick et al., 1977) to map surface currents.

The wave-height directional spectrum is extracted from a different part of the echo spectrum, that produced by the simultaneous interaction of two ocean wave trains. The mathematical expression for the echo spectrum in this case is an integral involving the wave-height directional spectrum twice; all of the mathematical factors appearing in this integral are determined from fundamental hydrodynamic and electromagnetic principles, and are completely known. Therefore, this integral equation can be inverted (and has been, with success) to give the wave-height directional spectrum.

Status of Sky-Wave Radars

HF radio signals of frequency less than 25 MHz can be totally reflected from the ionosphere, which is a layer of charged particles whose

effective reflective height (7 MHz and 25 MHz) lies between 100 and 300 km above the earth. Thus, a single reflection from the ionosphere can extend radar surveillance of the ocean to distances of 3000 km from the station.

The ionosphere, however, is a highly variable factor in the radar equation. Its density varies from day to night, summer to winter, with latitude, and in response to solar storms and their resulting emissions. Although average ionospheric conditions can be predicted or measured (by ionospheric soundings), temporal variations of the order of tens of seconds over spatial scales of the order of a few kilometers are largely unpredictable. These unknown variations in the effective reflecting layer produce Doppler spectral distortions in the signal of the same order as the expected variations produced by the sea echo. Therefore, the extraction of useful sea-state and current information is complicated by the ionosphere itself.

A joint research program of the Wave Propagation Laboratory (NOAA) and the Remote Measurement Laboratory (SRI International) has attempted to develop techniques for coping with the ionospheric distortions, and to determine the resulting accuracy of sky-wave radar for wide-area ocean wave measurements. Other countries also have active sky-wave programs for sea-state monitoring. A recent review of sky-wave sea-state radars is offered by Georges (1980).

Sky-wave radars have measured wave height to an accuracy of 3%, dominant (long-wave) direction to an accuracy of 3^{o}, and dominant period to an accuracy of 1.0 s (Lipa et al., 1981). In another situation, sky-wave radars measured wave height to an accuracy of 7%, and measured the five parameters of a nondirectional wave-height directional spectral model: agreement with buoy measurements was quite good (Maresca and Georges, 1980). However, both sets of experiments were conducted under favorable ionospheric conditions. Furthermore, the data were analyzed in a research mode in which echo time series taken in the field were later reduced and interpreted on computers in the laboratory.

Experiments to study the limitations, utility, and accuracy of real-time operation of sky-wave radars began in 1981. Software was developed that allowed the radar operator to scan a large ocean sector (out to 3000 km) at a pre-selected grid of points, in order to map wave height in real time. Preliminary analysis indicates that reasonable and accurate wave heights were mapped over several days as winter storms moved across the North Pacific. An exact assessment of accuracy is difficult to make. The only comparative wave-height information available for most of this wide area was provided by NOAA and Navy wave forecasts, and a few ship reports, both sources that are known to be quite inaccurate. All the general wave patterns recorded agree very well, however, demonstrating that ionospheric conditions can be sufficiently compensated to permit daily, real-time, synoptic maps of wave height, the single most important parameter of the wave-height directional spectrum. Wind direction maps (from sky-wave radar measurements of short wave directions) can also be made available in real time. Future real-time software should allow extraction of other important wave descriptors; it is not now clear, however, whether the entire

wave-height directional spectrum can be routinely measured with sky-wave radar, owing to ionospheric distortions.

Status of Ground-Wave Radars

The physical interaction of HF radar waves with the sea surface is the same for sky-wave radars and ground-wave radars. Therefore, if the distortions imposed on the sky-wave signal by the ionosphere can be removed, the remaining echo for both systems is effectively the same, and the methods of analysis discussed in this section are applicable to either system.

Narrow-Beam Ground-Wave Radars

The fundamental theoretical solutions for first- and second-order sea backscatter at high frequencies assume that a finite patch of ocean surface is viewed from a single, fixed direction (Barrick, 1972a,b, 1978; Barrick and Lipa, 1979a). This is what a narrow-beam radar does: an antenna whose aperture length is many wavelengths forms a beam whose angular width is a few degrees. The effective pulse width at a given time delay after pulse transmission thus defines an approximately rectangular patch of sea surface, whose dimensions typically vary from several kilometers to several tens of kilometers on a side. The requirement that antenna sizes be many wavelengths to form a narrow beam means the physical dimensions of antennas must be hundreds of meters at high frequencies.* Several such systems have been used in the past to obtain ground-wave HF sea echo. Because the mathematical expressions for the back-scattered signal spectrum are most straightforward for narrow-beam geometries, initial investigations of obtaining wave-height directional spectral parameters concentrated on measurements taken from those narrow-beam experiments.

If a given patch of sea can be observed by one radar from only a single direction, then only limited information about wave directional spectra can be obtained for that patch. There is a right-left ambiguity in wave direction about the line of sight. This means that when the directional spectrum is expanded in an angular Fourier series about the look direction to the patch, all odd (i.e., sine) coefficients in the series are indeterminate. Furthermore, some inaccuracy can occur in retrieving the even coefficients when the data are noisy (Lipa and Barrick, 1982). Nonetheless, success at extracting the most important wave directional spectral parameters has been achieved, vindicating the theoretical methods.

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*It is possible to circumvent the requirement for large antennas--for example, by synthetically forming a large aperture by driving a receiver along a road several kilometers long (Tyler et al., 1974). While of limited interest for research experiments, the methods are impractical for routine, long-term, operational monitoring.

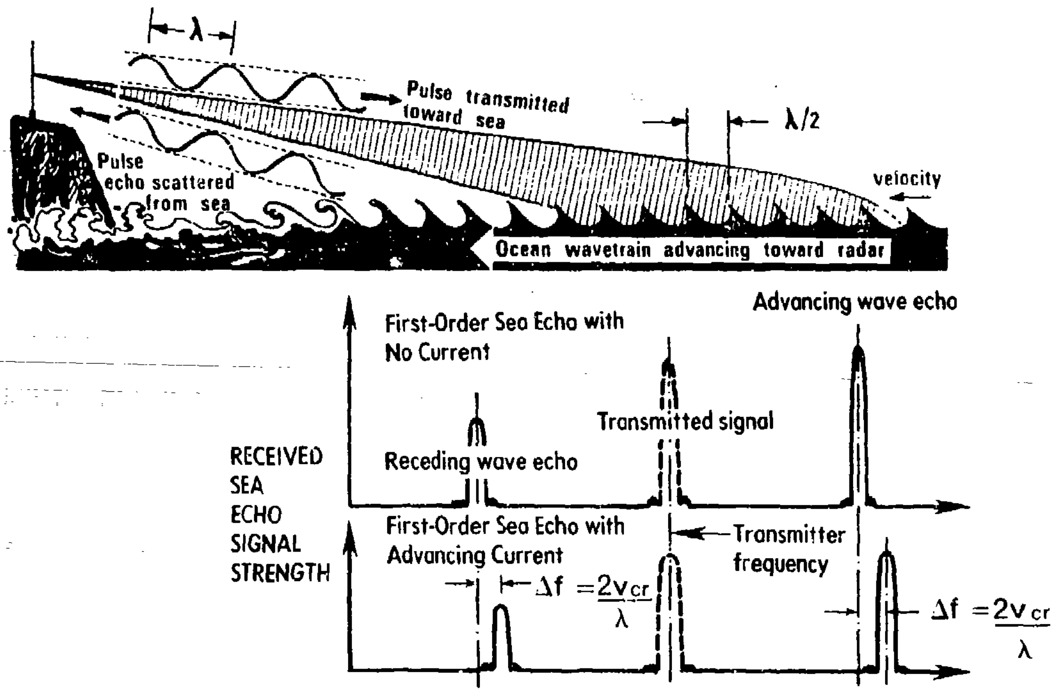

Figure 1 Sketch showing principles of first-order Bragg backscatter from the sea. Upper plot shows positions of echo energy in the signal spectrum from wave trains half the radar wavelength traveling toward and away from the radar. Lower plot shows symmetrical shift of these peaks by a current whose radial speed is v_{cr}.

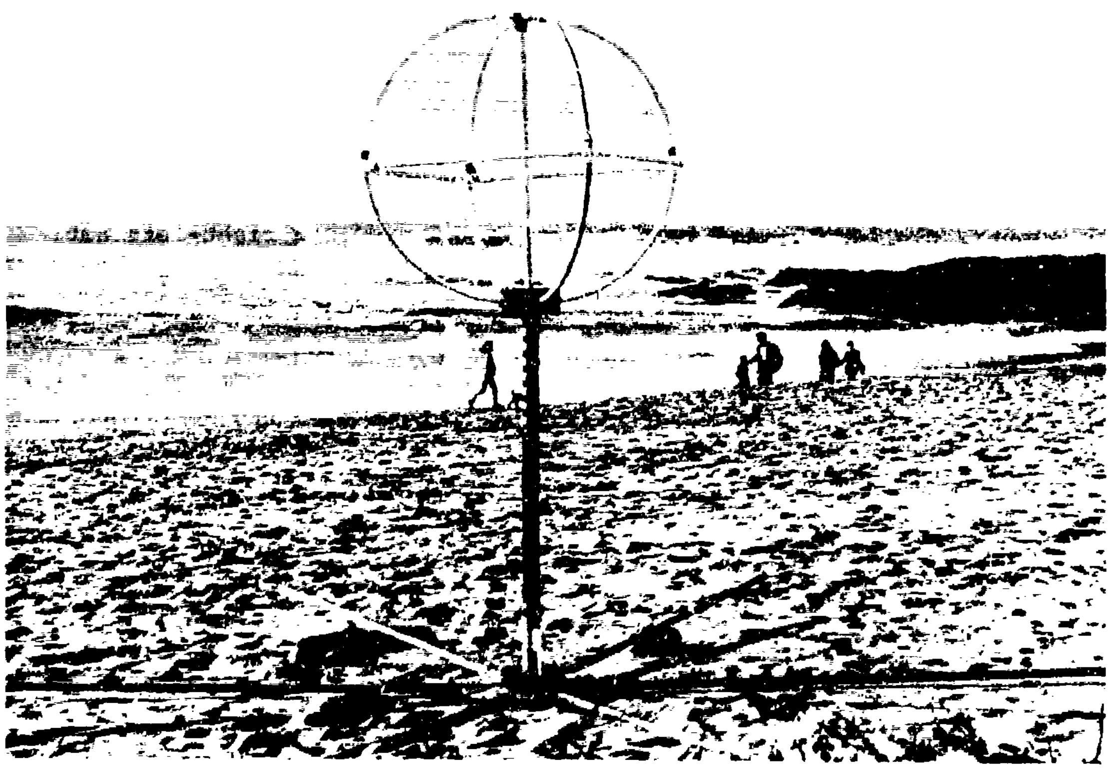

Figure 2 Photograph of compact crossed-loop/monopole antenna system for coastal wave-height directional spectral measurements, as operated at Pescadero, California, during January 1978. The antenna is less than 2 m tall.

Data from three narrow-beam radars have been analyzed and compared to heave-pitch-roll buoy requirements in the scatter area. One set was taken from a series of experiments done at San Clemente Island (off California) by a westward-looking NOAA/Navy/ITS ground-wave facility in 1972. A second was from a northwest-looking ground-wave system operated by Stanford University off Pescadero, California, between 1976 and 1978. The third set is narrow-beam sky-wave radar results from the Wide Aperture Radar Facility in California (owned by SRI International), selected for minimal ionospheric distortions.

Theoretical methods for inverting data from narrow-beam systems were developed by Lipa and Barrick (1980) for wave periods 10 s and greater. In this region, the integral equation is simplified by linearization. These methods were applied to the data from the three experiments by Lipa et al. (1981). The results confirm the theoretical methods, and show, for example, that wave height can be measured to an accuracy of $\pm 5\%$ (rms), wave period to ± 0.5 s (rms), and direction within 7° (rms).

Some external means of resolving the left-right directional ambiguity was of course required. Lipa (1978) developed and demonstrated inversion techniques for extracting accurate wave-height directional spectral information (based on the Stanford system) for wave periods down to 3 s, cases for which linearization of the integral equation is not possible.

Broad-Beam, Scanning, Ground-Wave Radars

Ground-wave radars with vertical polarization must have their antennas on the beach, as close to the seawater as possible, in order to achieve maximum distance. The large antenna sizes required for a narrow-beam system, as discussed above, make such systems uneconomical and environmentally unattractive for coastal or offshore sites. The most compact and unobtrusive antenna system that can provide the same angular information for wave spectra as a pitch-roll buoy is the crossed-loop/monopole technique discussed by Barrick and Lipa (1979b). Use of this configuration for both transmitting and receiving reduces the size of the antenna system further, and increases the angular resolution. A picture of such a system, operated at Pescadero, California, in 1978, is shown in Figure 2. Although this antenna system does not mechanically rotate, digital switching of signals among the three antenna elements (under microprocessor control) causes a broad beam to rotate in angle.

An HF radar with a compact antenna system such as this is ideally suited to coastal observations of wave-height directional spectra. In fact, the crossed-loop/monopole technique has been employed in two experiments for directional wave-field measurements: at Pescadero, California, in 1978, and at Duck, North Carolina, in 1980. Operation in coastal waters, however, requires accounting for a number of factors in analysis of the data.

Evaluation of the accuracy of the wave directional spectral measurements using the crossed-loop/monopole coastal HF radar under fetch-limited and current-distorted regimes is not yet completed.